Nanotechnology in a New Era of Strategic Competition

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Preparing GBU–16 aboard *USS Enterprise.*

U.S. Navy (Jacob L. Hollingsworth)

New technologies on the battlefield can alter the course of history and precipitate the rise or fall of nations. The advent of microelectromechanical systems (MEMS) coincides with what some regard as a revolution in military affairs (RMA), an onset of technological innovation that changes the nature of warfare. These tiny devices could be the revolution's enabling technology.

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In the mid-1990s, Admiral William Owens articulated the initial RMA concept as a *system of systems* that yields total *situational awareness*. An overarching systems architecture integrates an array of capabilities such as command and control, surveillance, reconnaissance, intelligence, and targeting. Under this integrated system, advantages of individual platforms and capabilities are fused into a powerful joint warfighting entity. As Andrew Marshall has predicted "The change will be profound . . . the new methods of warfare will be far more powerful than the old."[1]

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MEMS is a far-reaching technology with possible application to two broad military arenas: precision guided munitions (PGMs) and individual soldiers. The former represents the stand-off warfare likely to characterize future major regional conflicts while the latter represent a countertrend to manpower-intensive, close-in fighting likely to characterize military operations other than war. MEMS answer some criticisms of the revolution in military affairs—such as prohibitive cost—and expand the impact of the revolution by bringing its fruits to the level of the warfighter.

The developments examined below represent areas of great potential. They are in various stages of development, but their eventual realization is probable and cannot be ignored. Without serious consideration of MEMS, the Nation could loose its unchallenged military prominence like other states on the brink of RMAs who rested on past accomplishments or early leads.

Vision of New Technology

Richard Feynman delivered a speech in 1960, "There's Plenty of Room at the Bottom," which envisioned a technological world of the very small, where the units of construction were not blocks or circuits but atoms.[2] Nanotechnology, a term coined by Nobuhiko Taniguchi in 1974, is the technology of the ultrasmall: roughly the 1–100 nanometer or billionth of a meter (10^{-9} meters) range. Miniaturization will extend to mechanics and electronics. The field that combines the two microelectromechanical systems is known as MEMS in the United States. The vision statement of the Defense Advanced Research Projects Agency, which is spearheading research and development on MEMS, reads:

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The field of microelectromechanical systems is a revolutionary, enabling technology. It will merge the functions of compute, communicate, and power together with sense, actuate, and control to change completely the way people and machines interact with the physical world. Using an ever-expanding set of fabrications processes and materials, MEMS will provide the advantages of low power, low mass, low cost, and high functionality to integrated electromechanical systems both on the micro as well as the macroscale.

It must be stressed that MEMS are a multidisciplinary *approach* to design and fabrication, not simply a class of products. Its devices fall into three general categories: sensors, actuators, and mechanical components such as gears, cogs, and switches. These three categories demonstrate the ubiquity of this emerging potential. Virtually any mechanical or electronic device can be shrunk by replacing macroscale parts with MEMS.

But this technology is more than just miniaturization of existing systems. It allows for new functionality since the decrease in size facilitates the creation of new architectures. Through them an entire subsystem could be integrated on one chip. For example, one firm replaced an avionics component of 1,044 parts for F–22s with an equivalent MEMS component that had only 36 parts. This characteristic of multiple and mixed technology integration in MEMS devices and fabrication technologies may be especially relevant to the Armed Forces, which relies on a core competency of integrated global and local surveillance, communications, and data fusion.

Getting situation report, Culminating Phase Experiment.

2d Marine Division (D.R. Storms)

New High Ground

MEMS offer several dramatic advantages. The first is what makes the technology possible to begin with: universally accessible fabrication. These tiny parts are manufactured using the same processes as the integrated circuits of microchips

and can be made of silicon wafers. Because of the manufacturing technology, 10,000 MEMS can be built as easily as one. Correspondingly, ease of fabrication allows engineers to change the way they design systems. Economies of scale make production inexpensive. In fact, this massive reduction in cost is the main driver for research. For example, Raytheon Corporation wants to build a system of circuits for radios at 3 percent of the cost of macroscale systems. This product will shrink a bulky $200,000 system into a radio the size of a credit card for only $2,500. Multiplicity permits augmenting low-end systems with high-end technologies for greater performance and extended life. Many products can be upgraded, or many redundant systems can be included in the larger architecture for improved reliability and lowered maintenance demands. MEMS make advanced technology affordable in quantity.

Secondary effects will also reduce cost. Microscale systems require less energy to operate moving parts. Systems that run on lower power produce less heat, leading to fewer maintenance problems and a longer service life. Moreover, smaller systems that weigh less require less energy to propel. Other advantages stem from the physical properties of very small devices. Many use electrostatic energy for power, drastically reducing energy requirements.

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In some cases extreme sensitivity to the environment acts as a disadvantage, particularly in high temperatures. This special packaging challenge can account for more than 80 percent of the costs. Despite this problem, the demand for and development of this technology is continuing at an amazing pace. The Committee on Advanced Materials and Fabrication Methods for MEMS of the National Research Council contends that the technology makes possible the "implementation of fault-tolerant architectures that are modular, rugged, programmable, conventionally interfaced, and relatively insensitive to shock, vibration, and temperature variations."[3] Even though more research is needed in the field of MEMS packaging, solutions will be discovered.

MEMS is achieving a technological critical mass as more and more possible applications emerge, including:

- inertial measurement units
- signal processing
- distributed control of aerodynamic and hydrodynamic systems
- distributed sensors for condition-based maintenance and structural monitoring
- unattended sensors for tracking and surveillance
- mass data storage
- analytical instruments
- biomedical sensors
- optical fiber components and networks
- wireless communications
- active conformable surfaces for aircraft.

The range of uses suggests that MEMS is applicable to every aspect of military technology.

MEMS and PGMs

Among the many applications of this new technology is PGM enhancement. In the Persian Gulf War these munitions made such an impact that they became almost synonymous with the revolution in military affairs. Used against what war planners considered *strategic core* targets (C^3 assets, leadership facilities, and military support facilities), they were the weapons of choice.

Since then reliance on PGMs has only increased. Their accuracy makes them especially attractive. Collateral damage can be avoided. They permit selection of specific aimpoints for a given target to achieve desired objectives, perhaps merely disabling enemy assets rather than razing an entire site. Accuracy also increases the probability of a kill, meaning fewer munitions. Standoff capability, which keeps friendly forces away from well-defended targets, is another advantage.

Unfortunately the advantages of PGMs have not been fully realized in combat. The Persian Gulf War illustrated their limitations as well as their capabilities. They were not always as accurate as desired, and their sheer expense restricted their numbers. The conflict also revealed that simple countermeasures decrease effectiveness. The evidence suggests that Iraq housed some of its most valuable nuclear assets deep underground. It also frustrated the allies by placing military assets near populous areas or sites of religious or cultural significance or dispersing them in the desert every few days. Nevertheless, the low cost, small size, and light weight characteristics of microtechnology make it the ideal enabler for PGM systems, and integrating sensors, computers, accelerators, and actuators allows the systems to be custom designed for specific munitions. MEMS can make the components both smaller and cheaper. A typical missile accelerometer and gyroscope cost $1,000, but an equivalent microdevice costs $20.

With micronavigation components, many dumb munitions—howitzer, mortar, and rocket-fired—could be retrofitted and transformed into PGM-like weapons. Unguided rounds with a circular error probable of 250 meters could instantly improve to 64 meters. Smart rounds reduce the number required to destroy a target by a factor of ten.

Launching Tomahawk during Desert Fox.

U.S. Navy (Todd Cichonowicz)

Conducting surveillance operations with hunter sensor suite.

U.S. Army (Marshall Woods)

In addition to minimizing cost MEMS present several cost-imposing strategies to an enemy. High volumes of PGMs incentivize costly countermeasures. An enemy may invest heavily in anti-air warfare batteries, jamming capabilities, or underground facilities—essentially trading offensive for defensive investments. Moreover, dispersing and hiding targets requires sizable manpower, reduces efficiency in operations, and lowers morale. Cost-imposing strategies fostered by MEMS force an enemy to expend time, effort, and resources on defensive measures instead of offensive advancements that would in turn force the United States to develop countermeasures.

Sensor and fusing devices are an area in which MEMS could improve PGMs, for instance by eliminating unexploded ordnance that often causes friendly casualties and wastes resources. When a munition fails to detonate, a microaccelerometer could sense its impact with the earth and trigger a self-destruct mechanism. MEMS fusing/detonation devices offer greater reliability, which results in fewer duds.

Taking the Revolution to the Trenches

Planners emphasize PGMs, stealth aircraft, and other highly touted RMA platforms for use in

Marines during Urban Warrior '99.

Fleet Image Command, Pacific (Eric Logsdon)

conventional war. But many RMA supporters neglect individual soldiers as beneficiaries of the revolution through information, communication, situational awareness, survivability, and lethality.

New technologies are especially critical to lesser contingencies which are more manpower-intensive and where the value of firepower is diminished. Soldiers in this environment need better communications and intelligence—or situational awareness. Effective command and control is also vital, especially because complex operations typically involve small detached units. Overwhelming force, which can compensate for command and control weakness, will be unavailable. Moreover, such operations are increasingly joint and multilateral, placing greater strains and greater import on command and control.

But these technical needs clash with competing requirements for speed, agility, stealth, and mobility. Individual soldiers carry everything themselves, constraining weight and size. Taking technology to the individual level also demands more devices, limiting spending per unit. In light of such requirements, MEMS are the natural enabling technology for equipping soldiers.

Outfitting soldiers in mechanized suits was once the stuff of science fiction; but in the early 1990s the Army embarked on the Land Warrior project, with a vision of transforming each soldier into a Terminator III. The product director for the modular weapons system (MWS) in the Office of the U.S. Army Product Manager for Small Arms depicted the link between project and lethality:

With the advent of Land Warrior, you are integrating the infantryman's capabilities into the digitized battlefield without adversely affecting his performance, thereby multiplying his lethality through an ability to communicate what he sees and knows up to higher headquarters.[4]

The Land Warrior program realizes the idea of systems architecture, a system of systems. For instance the MWS component alone comprises subsystems such as close-combat optics, night-fighting sights, thermal weapon sights, laser rangefinder/compass/clinometer, camera modules, and combat identification equipment. The overall picture is an armored suit, special rifle, computerized helmet with a monocle display, and computers and electronic components wired throughout every part of the suit, with the ability to communicate remotely with other soldiers and headquarters.

But the program hit a snag. The suit weighs 80 pounds and proved too heavy for soldiers to maintain speed and agility in field tests. There were also problems with bulkiness and balance. Congress lost faith in the program and canceled funding.

The Land Warrior concept remains valid, but technical problems thwart its realization. In several areas MEMS research and development has already yielded results that could be speedily integrated into the Land Warrior or similar battle suit.

Communications. Using MEMS over the next few years, Raytheon is expected to produce a military radio receiver that weighs four ounces. It will work ten times longer than current models and require less maintenance. The receiver is part of a larger effort to shrink a four-channel radio, now weighing 10 pounds, to the size of a credit card.

Navigation. The MEMS inertial navigation system/global positioning system (INS/GPS) device that guides PGMs could also guide warriors. It could run on microwatts at a cost of $50 per unit. It could aid in locating friendly assets, interrogate from afar, and transmit its coordinates in response, greatly enhancing command and control.

Information display. The monocle visual display in the Land Warrior helmet shows maps, data, position, manuals, and orders from headquarters. Microtechnology makes possible a high-resolution, low-power display screen (0.5 to 5 inches), meeting mobility requirements and fitting into the larger computer network.

Chemical/biological warfare defense. The miniaturization of analytical instruments is a core MEMS technology. Although the United States has some chemical agent alarms, they are too bulky for individual use in the field. Microanalytical instruments could be made small enough for each soldier to carry several or integrated in a protective mask or mounted on equipment. Such a sensor might cost $25 and allow a five order of magnitude reduction in operating power.

Unmanned Aerial Vehicle (UAV). Lockheed Martin recently used MEMS to create a UAV that is only 6 inches long and weighs 3 ounces. Because of its light weight, soldiers could carry several disposable UAVs. One version of the MEMS model could provide reconnaissance, using radio signals to transmit real-time information from its camera to a display. Another version might couple CBW sensors to provide a stand-off chemical/biological warning system. Other versions of UAVs could jam enemy communications or designate targets for PGMs.

small, low-power, lightweight IFFs are possible using MEMS technology

Identification Friend or Foe (IFF). Military aircraft are equipped with a transmitter that when interrogated emits an identifying code to differentiate between threats and friendly forces. In the Persian Gulf no aircraft were downed by friendly fire. On the ground, however, 35 Americans died mainly because vehicles lacked IFF technology. Fortunately, small, low-power, lightweight IFFs are possible using MEMS technology. A passive, secure microdevice could be integrated into the uniform of each soldier and/or his equipment.

Analyzing readings from chemical/biological aerosol warning system.

U.S. Air Force (Wayne Clark)

Implications for Competitive Strategy

The U.S. military can be uniquely enhanced by MEMS because of its lead in the revolution in military affairs. Over the next decade or so, only America will be able to realize the revolution in its entirety. Successful innovation, combining new technology with operational advances, is key to retaining this lead and resulting political influence.

Other nations may acquire pieces of the revolution. Australia, Austria, Belgium, Britain, People's Republic of China, Denmark, Finland, France, Germany, Italy, Japan, The Netherlands, Poland, Russia, Sweden, and Switzerland are also researching nanotechnology. There is reason to believe that other countries may harness technological advantages to close the military gap between themselves and the United States. Because nanotechnology is dual use, regulating its export may be impossible. The same advantages that attract America and its allies to MEMS attract potential enemies. Though this pattern has been true for any nation experiencing revolutionary or even evolutionary advances in technology, MEMS is unique. The combination of low costs with high numbers of advanced weapons lures potential enemies perhaps more than the Pentagon. Rogue states, insurgents, and terrorists face greater resource constraints. These state and/or nonstate actors may perceive microtechnologies as their only way to compete with wealthier actors.

MEMS transcend traditional limits to technological proliferation. The cost of sophisticated weapons has traditionally been a great deterrent to their procurement. But microdevices cost less to acquire and operate through secondary effects such as reduced energy consumption and greater survivability. Their small size also makes them easier to smuggle or buy under the table. They are almost impossible to track, especially because they are dual use by nature and rudimentary to many systems. Both characteristics make global nonproliferation measures unlikely. How can a regime regulate simple valves or cogs—or commercial systems such as miniature cell phones or INS/GPS devices? Moreover, verification would be unworkable.

Even if a supply-side regime were attempted, the range of suppliers minimizes chances for success. Anyone who can manufacture a microchip

55th Signal Company (Russell J. Good)

Entering coordinates, Rapid Force Projection Initiative.

can create MEMS. The knowledge required is in the public domain. Thus MEMS obviate the traditional barrier of locating cooperative suppliers.

Since nuclear warheads, ballistic missiles, and chemical weapons are relatively unattainable MEMS will become more desirable. They can enhance existing unsophisticated weapons and also make sophisticated weapons easier to acquire. They can be perceived as a great equalizer.

The security ramifications of this new wave of technology are seldom addressed. Although some prophets warn of the apocalyptic dangers of self-replicating tiny machines, no one comments on the more immediate and pressing threats of proliferation or how enemies may take advantage of microtechnologies to use the revolution in military affairs against us.

MEMS offer opportunities to capitalize on new technology. PGMs exemplify the benefit of applying MEMS to existing RMA developments and how that application could lead to the full realization of their potential. The case of soldier-level warfare indicates how MEMS can extend advantages to areas of warfighting heretofore largely excepted from the revolution in military affairs.

It is unlikely that proliferation will completely disturb the balance in global military power. However, potential enemies could bypass our strengths and exploit weaknesses as well as raise the cost of intervention in regional conflicts. Technological advances, survivability, and redundancy by an enemy could deny a quick and painless victory, possibly deterring intervention in regional crises and thus eroding national leverage. The Nation would see its options limited as both human and economic costs of intervention increased.

The push for commercial applications as a way to reduce the research burden for military applications overlooks larger security ramifications and favors would-be enemies. Officials should review counterproliferation methods to reduce threats. Perhaps denying some key subtechnology could create a hurdle for MEMS proliferators. Packaging techniques, though not widely publicized yet and still in development, might offer such a solution.

The Armed Forces are poised to take advantage of the revolution in military affairs through microtechnology. Leaders must facilitate this process. The result will be broader capabilities that translate into greater political leverage and national security. But a plan to capitalize on a MEMS revolution must be two-pronged: the United States must utilize the technology and deny its use to any potential enemies. JFQ

NOTES

1 Barbara Starr, "Plotting Revolution at the Pentagon," *Jane's Defence Weekly*, vol. 23, no. 23 (June 10, 1995), p. 38.

2 Max Nelson and Calvin Shipbaugh, *The Potential of Nanotechnology for Molecular Manufacturing* (Santa Monica: The RAND Corporation, 1995), p. 3.

3 National Research Council, *Microelectromechanical System: Advanced Materials and Fabrication Methods* (Washington: National Academy Press, 1997), p. 13.

4 Scott Gourley, "Lethal Combination," *Jane's Defence Weekly*, vol. 30, no. 14 (October 7, 1998), pp. 39–42.